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Electroweak and Flavor Dynamics at Hadron Colliders

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Abstract

We catalog the principal signatures of electroweak and flavor dynamics at $\bar{p}p$ and pp colliders for use at the 1996 Snowmass Workshop on New Directions in High Energy Physics. The framework for dynamical symmetry breaking we assume is technicolor, with a walking coupling α_{TC}, and extended technicolor. The reactions discussed occur mainly at subprocess energies $\sqrt{\hat{s}} \lesssim 1\,\mathrm{TeV}$. They include production of color-singlet and octet technirhos and their decay into pairs of technipions, longitudinal weak bosons, or jets. Technipions, in turn, decay predominantly into heavy fermions. Many of these signatures are also expected to occur in topcolor-assisted technicolor. Several particles specific to this new scenario are discussed. Additional signatures of flavor dynamics, associated with quark and lepton substructure, may be sought in excess production rates for high E_T and invariant mass dijets and dileptons. An important feature of these processes is that they exhibit fairly central angular and rapidity distributions.

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1. Plan

This document lists the major signals for dynamical electroweak and flavor symmetry breaking in experiments at the Tevatron Collider and the Large Hadron Collider. It was prepared to help guide studies at the 1996 Snowmass Summer Study. The motivations for these studies are clear: We do not know the mechanism of electroweak symmetry breaking nor the physics underlying flavor and its symmetry breaking. The dynamical scenarios whose signals we catalog provide an attractive theoretical alternative to perturbative supersymmetry models. At the same time, they give experimentalists a set of high-p_T signatures that challenge heavy-flavor tagging, tracking and calorimetry—detector subsystems somewhat complementary to those tested by supersymmetry searches. Finally, many of the most important signs of electroweak and flavor dynamics have sizable rates and are relatively easily detected in hadron collider experiments. Extensive searches are underway in both Tevatron Collider collaborations, CDF and DØ. We hope that this document will help the ATLAS and CMS Collaborations begin their studies.

Section 2 contains a brief overview of technicolor and extended technicolor, the best theoretical basis we have for dynamical electroweak and flavor symmetry breaking. This discussion includes summaries of the main ideas that have developed over the past decade: walking technicolor, multiscale technicolor, and topcolor-assisted technicolor.

Hadron collider signals of technicolor involve production of technipions via $\bar{q}q$ annihilation and gg fusion. These technipions include the longitudinal weak bosons W_L and Z_L as well as the pseudo-Goldstone bosons π_T of dynamical symmetry breaking. The π_T are generally expected to have Higgs-boson-like couplings to fermions and, therefore, to decay to heavy, long-lived quarks and leptons. The subprocess production cross sections for color-singlet technipions are listed for simple models in Section 3.1. The most promising processes involve production of an isovector technirho ρ_{T1} resonance and its subsequent decay into technipion pairs. The most important subprocesses for colored technihadrons are discussed in Section 3.2. These involve a color-octet s-channel resonance with the same quantum numbers as the gluon; this technirho ρ_{T8} dominates colored technipion pair production. It is possible that $M_{\rho_{T8}} < 2M_{\pi_T}$, in which case $\rho_{T8} \rightarrow \bar{q}q$, gg, appearing as a resonance in dijet production. The main signatures of topcolor-assisted technicolor, top-pions π_t and the color-octet V_8 and singlet Z' of broken topcolor gauge symmetries, are described in section 3.3.

In Section 4, we motivate and discuss the main "low-energy" signatures of quark and lepton substructure—excess production of high-E_T jets and high invariant mass dileptons.

Cross sections are presented for a simple form of the contact interaction induced by substructure. We re-emphasize that the shapes of angular distributions are an important test for new physics as the origin of such excesses. We also stress the need to study the effect of other forms for the contact interactions.

This is not intended to be a complete survey of electroweak and flavor dynamics signatures accessible at hadron colliders. We have limited our discussion to processes with the largest production cross sections and most promising signal-to-background ratios. Studies of these processes at Snowmass will go far toward building a cadre of experts to carry out the most far-ranging simulations of these processes and their observability in the detectors now being designed and built. Even for the processes we list, we have not provided detailed cross sections for signals and backgrounds. Signal rates depend on masses and model parameters; they and the backgrounds also depend strongly on detector capabilities. Experimenters in the detector collaborations will have to carry out these studies. At the end of this document, I have provided a table summarizing the main processes, sample cross sections at the Tevatron and LHC, and the names of CDF and DØ members who have experience in these searches and have graciously agreed to provide guidance for the simulations at Snowmass.

2. Technicolor and Extended Technicolor

Technicolor—a strong interaction of fermions and gauge bosons at the scale $\Lambda_{TC} \sim 1\,\mathrm{TeV}$—is a scenario for the dynamical breakdown of electroweak symmetry to electromagnetism [1]. Based on the similar phenomenon of chiral symmetry breakdown in QCD, technicolor is explicitly defined and completely natural. To account for the masses of quarks, leptons, and Goldstone "technipions" in such a scheme, technicolor, ordinary color, and flavor symmetries are embedded in a larger gauge group, called extended technicolor (ETC) [2]. The ETC symmetry is broken down to technicolor and color at a scale $\Lambda_{ETC} = \mathcal{O}(100\,\mathrm{TeV})$. Technicolor with extended technicolor constitute a scenario for electroweak and flavor symmetry breakdown that does not rely on mystical incantations about physics in hidden sectors at inaccessibly high energy scales. Indeed, as we describe below, many signatures of ETC are expected in the energy regime of 100 GeV to 1 TeV, the region covered by the Tevatron and Large Hadron Colliders. For a review of technicolor developments up through 1993, see Ref. [3].

The principal signals in hadron collider experiments of "classical" technicolor and extended technicolor were discussed in Ref. [4]. In the minimal technicolor model, containing just one technifermion doublet, the only prominent signals in high energy collider experiments are the modest enhancements in longitudinally-polarized weak boson production. These are the s-channel color-singlet technirho resonances near 1.5–2 TeV: $\rho^0_{T1} \to W^+_L W^-_L$ and $\rho^\pm_{T1} \to W^\pm_L Z^0_L$. The small $O(\alpha^2)$ cross sections of these processes and the difficulty of reconstructing weak-boson pairs with reasonable efficiency make observing these enhancements a challenge. Nonminimal technicolor models are much more accessible because they have a rich spectrum of lower energy technirho vector mesons and technipion (π_T) states into which they may decay. In the one-family model, containing one isodoublet each of color-triplet techniquarks (U, D) and color-singlet technileptons (N, E), the technifermion chiral symmetry is $SU(8) \otimes SU(8)$. There are 63 ρ_T and π_T, classified according to how they transform under ordinary color $SU(3)$ times weak isospin $SU(2)$. The technipions are $\pi^{0\prime}_T \in (1,1)$; $W^\pm_L, Z^0_L$ and $\pi^\pm_T, \pi^0_T \in (1,3)$; color octets $\eta_T \in (8,1)$ and $\pi^\pm_{T8}, \pi^0_{T8} \in (8,3)$; and color-triplet leptoquarks $\pi_{Q\bar{L}}$, $\pi_{L\bar{Q}} \in (3,3) \oplus (3,1) \oplus (\bar{3},3) \oplus (\bar{3},1)$. The ρ_T belong to the same representations.

Because of the conflict between constraints on flavor-changing neutral currents and the magnitude of ETC-generated quark, lepton and technipion masses, classical technicolor was superseded a decade ago by "walking" technicolor. In this kind of gauge theory, the strong technicolor coupling α_{TC} runs very slowly for a large range of momenta, possibly all the way up to the ETC scale—which must be several 100 TeV to suppress FCNC. This slowly-running coupling permits quark and lepton masses as large as a few GeV to be generated from ETC interactions at this very high scale [5].

Walking technicolor models require a large number of technifermions in order that α_{TC} runs slowly. These fermions may belong to many copies of the fundamental representation of the technicolor gauge group, to a few higher dimensional representations, or to both. This fact inspired a new kind of model, "multiscale technicolor", and a very different phenomenology [6]. In multiscale models, there typically are two widely separated scales of electroweak symmetry breaking, with the upper scale set by the weak decay constant $F_\pi = 246\,\mathrm{GeV}$. Technihadrons associated with the lower scale may be so light that they are within reach of the Tevatron collider; they certainly are readily produced *and detected* at the LHC. Because of technipion mass enhancements in walking technicolor models, some $\rho_T \to \pi_T \pi_T$ decay channels may be closed. If this happens with color-octet ρ_{T8}, these copiously produced states appear as resonances in dijet production. If the $\pi_T \pi_T$ channels

are open, they are resonantly produced at large rates—of order 10 pb at the Tevatron and several nanobarns at the LHC—and, given the recent successes and coming advances in heavy flavor detection, many of these technipions should be reconstructable in the hadron collider environment.

Another major advance in technicolor came in the past two years with the discovery of the top quark [7]. Theorists have concluded that ETC models cannot explain the top quark's large mass without running afoul of either cherished notions of naturalness or experimental constraints from the ρ parameter and the $Z \to \bar{b}b$ decay rate [8], [9]. This state of affairs has led to "topcolor-assisted technicolor" (TC2). In TC2, as in top-condensate models of electroweak symmetry breaking [10], [11], almost all of the top quark mass arises from a new strong "topcolor" interaction. To maintain electroweak symmetry between top and bottom quarks and yet not generate $m_b \simeq m_t$, the topcolor gauge group is generally taken to be $SU(3) \otimes U(1)$, with the $U(1)$ providing the difference between top and bottom quarks. Then, in order that topcolor interactions be natural—i.e., that their energy scale not be far above m_t—and yet not introduce large weak isospin violation, it is necessary that electroweak symmetry breaking is still due mainly to technicolor interactions [12]. In TC2 models, ETC interactions are still needed to generate the light and, possibly, bottom quark masses, contribute a few GeV to m_t, and give mass to many technipions. The scale of ETC interactions still must be hundreds of TeV to suppress FCNC and, so, the technicolor coupling must still walk. Two recent papers developing the TC2 scenario are in Ref. [13]. Although the phenomenology of TC2 is in its infancy, it is expected to share general features with multiscale technicolor—many technihadron states, some carrying ordinary color, some within range of the Tevatron, and almost all easily produced and detected at the LHC at moderate luminosities.

3. Signatures for Technicolor and Extended Technicolor

We assume that the technicolor gauge group is $SU(N_{TC})$ and that its gauge coupling walks. A minimal, one-doublet model can have a walking α_{TC} only if the technifermions belong to a large non-fundamental representation. For nonminimal models, we generally consider the phenomenology of the lighter technifermions transforming according to the fundamental (N_{TC}) representation; some of these may also be ordinary color triplets. In almost all respects, walking models are very different from QCD with a few fundamental

$SU(3)$ representations. Thus, arguments based on naive scaling from QCD and on large-N_{TC} certainly are suspect. In TC2, there is no need for large isospin splitting in the technifermion sector associated with the top-bottom mass difference. Thus, we can assume negligible splitting; this simplifies our discussion.

The $\rho_{T1} \to W^+W^-$ and $W^\pm Z^0$ signatures of the minimal model were discussed in Ref. [4]. The principal change due to the large representation and walking is that scaling the $\rho_{T1} \to \pi_T\pi_T$ coupling α_{ρ_T} from QCD is questionable. It may be smaller than usually assumed and lead to a narrower ρ_{T1}. There is also the possibility that, because of its large mass (naively, 1.5–2 TeV), the ρ_{T1} has a sizable branching ratio to four-weak-boson final states. To my knowledge, neither of these possibilities has been investigated. Enhanced weak-boson pair production in hadron collisions will be studied at Snowmass by the working group on Signals for Strong Electroweak Symmetry Breaking.

From now on, we consider only nonminimal models which, we believe, are much more likely to lead to a satisfactory walking model. They have a rich phenomenology with many diverse, relatively accessible signals. The masses of technipions in these models arise from broken ETC and ordinary color interactions. In walking models we have studied, they lie in the range 100–600 GeV; technirho vector meson masses are expected to lie between 200 and 1000 GeV (see, e.g., Ref. [6]).

3.1. Color-Singlet Technipion Production

Color-singlet technipions, including longitudinal weak bosons W_L and Z_L, are pair-produced via the Drell-Yan process in hadron collisions. Their $\mathcal{O}(\alpha^2)$ production rates at the Tevatron and LHC are unobservably small compared to backgrounds *unless* there are fairly strong color-singlet technirho resonances not far above threshold. To parameterize the cross sections simply, we consider a model containing two isotriplets of technipions which mix $W_L^\pm$, Z_L^0 with a triplet of mass-eigenstate technipions $\pi_T^{\pm,0}$ [6], [14]. We assume that the lighter isotriplet ρ_{T1} decays into pairs of the state $|\Pi_T\rangle = \sin\chi\,|W_L\rangle + \cos\chi\,|\pi_T\rangle$, leading to the processes

$$\begin{aligned} q\bar{q}' &\to W^\pm \to \rho_{T1}^\pm \to\; W_L^\pm Z_L^0; \quad W_L^\pm \pi_T^0,\; \pi_T^\pm Z_L^0; \quad \pi_T^\pm \pi_T^0 \\ q\bar{q} &\to \gamma, Z^0 \to \rho_{T1}^0 \to\; W_L^+ W_L^-; \quad W_L^\pm \pi_T^\mp; \quad \pi_T^+ \pi_T^- \,. \end{aligned} \tag{3.1}$$

The s-dependent ρ_{T1} partial widths are given by (assuming no other channels, such as colored techipion pairs, are open)

$$\Gamma(\rho_{T1} \to \pi_A \pi_B; s) = \frac{2\alpha_{\rho_T} \mathcal{C}^2_{AB}}{3} \, \frac{p^3_{AB}}{s} \,, \tag{3.2}$$

where p_{AB} is the technipion momentum and $\mathcal{C}^2_{AB} = \sin^4\chi,\ 2\sin^2\chi\cos^2\chi,\ \cos^4\chi$ for $\pi_A\pi_B = W_L W_L,\ W_L\pi_T + \pi_T W_L,\ \pi_T\pi_T$, respectively. The $\rho_{T1} \to \pi_T\pi_T$ coupling α_{ρ_T} obtained by naive scaling from QCD is [4]

$$\alpha_{\rho_T} = 2.91 \left(\frac{3}{N_{TC}}\right) . \tag{3.3}$$

Technipion decays are mainly induced by ETC interactions which couple them to quarks and leptons. These couplings are Higgs-like, and so technipions are expected to decay into heavy fermion pairs:

$$\begin{aligned}
\pi^0_T &\to \begin{cases} b\bar b & \text{if } M_{\pi_T} < 2m_t, \\ t\bar t & \text{if } M_{\pi_T} > 2m_t; \end{cases} \\
\pi^+_T &\to \begin{cases} c\bar b \text{ or } c\bar s,\ \tau^+\nu_\tau & \text{if } M_{\pi_T} < m_t + m_b, \\ t\bar b & \text{if } M_{\pi_T} > m_t + m_b. \end{cases}
\end{aligned} \tag{3.4}$$

An important caveat to this rule applies to TC2 models. There, only a few GeV of the top mass arises from ETC interactions. Then, the $b\bar b$ mode competes with $t\bar t$ for π^0_T; $c\bar b$ or $c\bar s$ compete with $t\bar b$ for π^+_T. Note that, since the decay $t \to \pi^+_T b$ is strongly suppressed in TC2 models, the π^+_T can be much lighter than the top quark.

The $\rho_{T1} \to \pi_A\pi_B$ cross sections are well-approximated by

$$\frac{d\hat\sigma(q_i\bar q_j \to \rho^{\pm,0}_{T1} \to \pi_A\pi_B)}{dz} = \frac{\pi\alpha^2 p^3_{AB}}{3\hat s^{5/2}} \, \frac{M^4_{\rho_{T1}} \ (1-z^2)}{(\hat s - M^2_{\rho_{T1}})^2 + \hat s \Gamma^2_{\rho_{T1}}} \, A^{\pm,0}_{ij}(\hat s)\mathcal{C}^2_{AB} \,, \tag{3.5}$$

where $\hat s$ is the subprocess energy, $z = \cos\theta$ is the π_A production angle, and $\Gamma_{\rho_{T1}}$ is the $\hat s$-dependent total width of ρ_{T1}. Ignoring Kobayashi-Maskawa mixing angles, the factors $A^{\pm,0}_{ij} = \delta_{ij} A^{\pm,0}$ are

$$\begin{aligned}
A^{\pm} &= \frac{1}{4\sin^4\theta_W}\left(\frac{\hat s}{\hat s - M^2_W}\right)^2 \\
A^0 &= \left[Q_i + \frac{2\cos 2\theta_W}{\sin^2 2\theta_W}\,(T_{3i} - Q_i\sin^2\theta_W)\left(\frac{\hat s}{\hat s - M^2_Z}\right)\right]^2 \\
&\quad + \left[Q_i - \frac{2Q_i\cos 2\theta_W \sin^2\theta_W}{\sin^2 2\theta_W}\left(\frac{\hat s}{\hat s - M^2_Z}\right)\right]^2 .
\end{aligned} \tag{3.6}$$

Here, Q_i and T_{3i} are the electric charge and third component of weak isospin for $q_{iL,R}$. Production rates of several picobarns increase by 5–10 at the LHC; see Table 1.

In the one-family and other models containing colored as well as color-singlet technifermions, there are singlet and octet technipions that are electroweak isosinglets commonly denoted $\pi_T^{0\prime}$ and η_T. These are singly-produced in gluon fusion. Depending on the technipion's mass, it is expected to decay to $\bar{b}b$ (and, possibly, gg) or to $\bar{t}t$ [4], [15]. With $\Pi^0 = \pi_T^{0\prime}$ or η_T, and with constituent technifermions transforming according to the N_{TC} representation of $SU(N_{TC})$, the decay rates are

$$\begin{aligned} \Gamma(\Pi^0 \to gg) &= \frac{\mathcal{C}_\Pi \alpha_S^2\, N_{TC}^2\, M_\Pi^3}{128\,\pi^3\, F_T^2}\,, \\ \Gamma(\Pi^0 \to \bar{q}q) &= \frac{\gamma_q^2\, m_q^2\, M_\Pi\, \beta_q}{16\pi F_T^2}\,. \end{aligned} \tag{3.7}$$

Here, $\beta_q = \sqrt{1 - 4m_q^2/M_\Pi^2}$ is the quark velocity. The $SU(3)$-color factor $\mathcal{C}_\Pi$ is determined by the triangle-anomaly graph for $\Pi^0 \to gg$. In the one-family model, $\mathcal{C}_\Pi = \frac{4}{3}$ for the singlet $\pi_T^{0\prime}$ and $\frac{5}{3}$ for the octet η_T; values of $\mathcal{O}(1)$ are expected in other models. The technipion decay constant F_T is discussed below. The dimensionless factor γ_q allows for model dependence in the technipions' couplings to $\bar{q}q$. In classical ETC models, we expect $|\gamma_q| = \mathcal{O}(1)$. In TC2 models, $|\gamma_q| = \mathcal{O}(1)$ for the light quarks and, possibly, the b-quark, but $|\gamma_t| = \mathcal{O}(\text{few GeV}/m_t) \ll 1$; there will be no η_T enhancement of $\bar{t}t$ production in topcolor-assisted technicolor.

The gluon fusion cross section for production and decay of Π^0 to heavy $\bar{q}q$ is isotropic:

$$\frac{d\hat{\sigma}(gg \to \Pi^0 \to \bar{q}q)}{dz} = \frac{\pi \mathcal{N}_C}{32}\, \frac{\Gamma(\Pi^0 \to gg)\, \Gamma(\Pi^0 \to \bar{q}q)}{(\hat{s} - M_\Pi^2)^2 + \hat{s}\, \Gamma_{\Pi^0}^2}\,, \tag{3.8}$$

where $\mathcal{N}_C = 1$ (8) for $\pi_T^{0\prime}$ (η_T). The decay rates and cross sections are contolled by the technipion decay constant F_T. In the standard one-family model, $F_T = 123\,\text{GeV}$ and the enhancements in $\bar{q}q$ production are never large enough to see above background (unless N_{TC} is unreasonably large). In multiscale models and, we expect, in TC2 models, F_T may be considerably smaller. For example, in the multiscale model considered in Ref. [6], $F_T = 30$–$50\,\text{GeV}$; in the TC2 model of Ref. [13], $F_T = 80\,\text{GeV}$. Since the total hadronic cross section,

$$\sigma(pp^\pm \to \Pi^0 \to \bar{q}q) \simeq \frac{\pi^2}{2s}\, \frac{\Gamma(\Pi^0 \to gg)\, \Gamma(\Pi^0 \to \bar{q}q)}{M_\Pi\, \Gamma_{\Pi^0}} \int d\eta_B\, f_g^p\!\left(\frac{M_\Pi}{\sqrt{s}} e^{\eta_B}\right) f_g^p\!\left(\frac{M_\Pi}{\sqrt{s}} e^{-\eta_B}\right), \tag{3.9}$$

scales as $1/F_T^2$, small decay constants may lead to observable enhancements in $\bar{t}t$ production in standard multiscale technicolor and in $\bar{b}b$ production in TC2. Sample rates are given in Table 1.

In models containing colored technifermions, color-singlet technipions are also pair-produced in the isospin $I = 0$ channel via gluon fusion. This process involves intermediate states of color-triplet and octet technipions. Again, the subprocess cross section is isotropic; it is given by [16].

$$\begin{aligned}
\frac{d\hat{\sigma}(gg \to \pi_T^+ \pi_T^-)}{dz} &= 2\frac{d\hat{\sigma}(gg \to \pi_T^0 \pi_T^0)}{dz} \\
&= \frac{\alpha_S^2 \beta}{2^{15}\pi^3 F_T^4 \hat{s}} \left| T(R) \, \left[C_R \, \left(\hat{s} - \tfrac{2}{3}(2M_R^2 + M_{\pi_T}^2)\right) + D_R \right] \, \left(1 + 2\mathcal{I}(M_R^2, \hat{s})\right) \right|^2 .
\end{aligned} \tag{3.10}$$

Here, $\beta = 2p/\sqrt{\hat{s}}$ is the technipion velocity. The sum is over $SU(3)$ representations $R = 3, 8$ of the π_T and $T(R)$ is the trace of the square of their $SU(3)$-generator matrices: $T(R) = \frac{1}{2}$ for triplets (dimension $d(R) = 3$), 3 for octets ($d(R) = 8$). The factors C_R and D_R are listed in Table 2 for the one–family model and a multiscale model. The integral $\mathcal{I}$ is

$$\begin{aligned}
\mathcal{I}(M^2, s) &\equiv \int_0^1 dx\, dy \, \frac{M^2}{xys - M^2 + i\epsilon} \, \theta(1 - x - y) \\
&= \begin{cases} -M^2/2s \left[\pi - 2\arctan\sqrt{4M^2/s - 1}\right]^2 & \text{for } s < 4M^2 \\ M^2/2s \left[\ln\left(\frac{1+\sqrt{1-4M^2/s}}{1-\sqrt{1-4M^2/s}}\right) - i\pi\right]^2 & \text{for } s > 4M^2 \ . \end{cases}
\end{aligned} \tag{3.11}$$

The rates at the Tevatron are at most comparable to those enhanced by technirhos; they are considerably greater at the the LHC because the fusing gluons are at low x (see Table 1). An interesting feature of this cross section is that the $\pi_T \pi_T$ invariant mass distribution peaks near the color-triplet and octet technipion thresholds, which can be well above $2M_{\pi_T}$. It is possible that mixed modes such as $W_L^\pm \pi_T^\mp$ and $Z_L \pi_T^0$ are also produced by gluon fusion, with the rates involving mixing angles such as χ in Eq. (3.5).

3.2. Color-Octet Technirho Production and Decay to Jets and Technipions

Models with an electroweak doublet of color-triplet techniquarks (U, D) have an octet of $I = 0$ technirhos, ρ_{T8}, with the same quantum numbers as the gluon. The ρ_{T8} are produced strongly in $\bar{q}q$ and gg collisions. Assuming, for simplicity, one doublet (N, E) of color-singlet technileptons (as in the one-family model), there are the 63 technipions listed

in Section 2. The color-singlet and octet technipions decay as in Eq. (3.4) above. The leptoquark decay modes are expected to be

$$\begin{aligned}
\pi_{U\bar{N}} &\to \begin{cases} c\bar{\nu}_\tau & \text{if } M_{\pi_T} < m_t, \\ t\bar{\nu}_\tau & \text{if } M_{\pi_T} > m_t; \end{cases} \\
\pi_{U\bar{E}} &\to \begin{cases} c\tau^+ & \text{if } M_{\pi_T} < m_t, \\ t\tau^+ & \text{if } M_{\pi_T} > m_t; \end{cases} \\
\pi_{D\bar{N}} &\to b\bar{\nu}_\tau\,; \\
\pi_{D\bar{E}} &\to b\tau^+\,.
\end{aligned} \tag{3.12}$$

The caveat regarding technipion decays to top quarks in TC2 models still applies.

There are two possibilities for ρ_{T8} decays [6]. If walking technicolor enhancements of the technipion masses close off the $\pi_T\pi_T$ channels, then $\rho_{T8} \to \bar{q}q,\, gg \to$ jets. The color-averaged $\mathcal{O}(\alpha_S^2)$ cross sections are given by

$$\begin{aligned}
\frac{d\hat{\sigma}(\bar{q}_i q_i \to \bar{q}_i q_i)}{dz} &= \frac{2\pi\alpha_S^2}{9\hat{s}}\left\{\left|\mathcal{D}_{gg}(\hat{s})\right|^2\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right) - \tfrac{2}{3}\,\mathrm{Re}\,\mathcal{D}_{gg}(\hat{s})\left(\tfrac{\hat{u}^2}{\hat{s}\hat{t}}\right) + \tfrac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right\}; \\
\frac{d\hat{\sigma}(\bar{q}_i q_i \to \bar{q}_j q_j)}{dz} &= \frac{2\pi\alpha_S^2}{9\hat{s}}\left|\mathcal{D}_{gg}(\hat{s})\right|^2\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right); \\
\frac{d\hat{\sigma}(\bar{q}_i q_i \to gg)}{dz} &= \frac{64}{9}\frac{d\hat{\sigma}(gg \to q_i\bar{q}_i)}{dz} = \frac{4\pi\alpha_S^2}{3\hat{s}}\left\{\left|\mathcal{D}_{gg}(\hat{s})-1\right|^2\frac{2\hat{u}\hat{t}}{\hat{s}^2} + \tfrac{4}{9}\left(\tfrac{\hat{u}}{\hat{t}}+\tfrac{\hat{t}}{\hat{u}}\right) - \tfrac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right\}; \\
\frac{d\hat{\sigma}(gg \to gg)}{dz} &= \frac{9\pi\alpha_S^2}{4\hat{s}}\left\{3 - \frac{\hat{u}\hat{t}}{\hat{s}^2} - \frac{\hat{t}\hat{s}}{\hat{u}^2} - \frac{\hat{s}\hat{u}}{\hat{t}^2}\right. \\
&\qquad \left. + \tfrac{1}{4}\left|\mathcal{D}_{gg}(\hat{s})-1\right|^2\left(\tfrac{\hat{u}-\hat{t}}{\hat{s}}\right)^2 - \tfrac{1}{4}\mathrm{Re}(\mathcal{D}_{gg}(\hat{s})-1)\,\tfrac{(\hat{u}-\hat{t})^2}{\hat{u}\hat{t}}\right\}; \\
\frac{d\hat{\sigma}(q_i q_j \to q_i q_j)}{dz} &= \frac{d\hat{\sigma}(\bar{q}_i\bar{q}_j \to \bar{q}_i\bar{q}_j)}{dz} = \frac{d\hat{\sigma}(q_i\bar{q}_j \to q_i\bar{q}_j)}{dz} = \frac{2\pi\alpha_S^2}{9\hat{s}}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right); \\
\frac{d\hat{\sigma}(q_i q_i \to q_i q_i)}{dz} &= \frac{d\hat{\sigma}(\bar{q}_i\bar{q}_i \to \bar{q}_i\bar{q}_i)}{dz} = \frac{2\pi\alpha_S^2}{9\hat{s}}\left\{\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} + \frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2} - \tfrac{2}{3}\tfrac{\hat{s}^2}{\hat{u}\hat{t}}\right\}; \\
\frac{d\hat{\sigma}(g q_i \to g q_i)}{dz} &= \frac{d\hat{\sigma}(g\bar{q}_i \to g\bar{q}_i)}{dz} = \frac{\pi\alpha_S^2}{2\hat{s}}\left(\hat{s}^2+\hat{u}^2\right)\left(\frac{1}{\hat{t}^2} - \frac{4}{9\hat{s}\hat{u}}\right).
\end{aligned} \tag{3.13}$$

Here, $z = \cos\theta$, $\hat{t} = -\frac{1}{2}\hat{s}(1-z)$, $\hat{u} = -\frac{1}{2}\hat{s}(1+z)$ and it is understood that $q_i \neq q_j = u, d, c, s, b$ contribute to dijet events. Only the s-channel gluon propagator was modified to include the ρ_{T8} resonance. Here and below, we use the dimensionless propagator factors $\mathcal{D}_{gg}$ and $\mathcal{D}_{g\rho_T}$

$$\begin{aligned}
\mathcal{D}_{gg}(s) &= \frac{s - M^2_{\rho_{T8}} + i\sqrt{s}\,\Gamma_{\rho_{T8}}(s)}{s(1-2\alpha_S(s)/\alpha_{\rho_T}) - M^2_{\rho_{T8}} + i\sqrt{s}\,\Gamma_{\rho_{T8}}(s)}\,, \\
\mathcal{D}_{g\rho_T}(s) &= \frac{s}{s(1-2\alpha_S(s)/\alpha_{\rho_T}) - M^2_{\rho_{T8}} + i\sqrt{s}\,\Gamma_{\rho_{T8}}(s)}\,.
\end{aligned} \tag{3.14}$$

The s-dependent ρ_{T8} width in this case is the sum of (allowing for multijet $\bar{t}t$ final states, assumed light compared to $\sqrt{s}$)

$$\begin{aligned}
\sum_{i=1}^{6} \Gamma(\rho_{T8} \to \bar{q}_i q_i) &= \frac{6}{3}\frac{\alpha_S^2(s)}{\alpha_{\rho_T}}\sqrt{s}\,, \\
\Gamma(\rho_{T8} \to gg) &= \frac{\alpha_S^2(s)}{\alpha_{\rho_T}}\sqrt{s}\,.
\end{aligned} \tag{3.15}$$

A search for the dijet signal of ρ_{T8} has been carried out by the CDF Collaboration; see Ref. [17] for a detailed discussion of expected signal and background rates. Rough signal-to-background estimates are given in Table 1. They are sizable at the Tevatron and LHC, but are sensitive to jet energy resolutions.

Colored technipions are pair-produced in hadron collisions through quark-antiquark annihilation and gluon fusion. If the $\rho_{T8} \to \pi_T\pi_T$ decay channels are open, this production is resonantly enhanced. The subprocess cross sections, averaged over initial colors and summed over the colors B, C of technipions, are given by

$$\sum_{B,C} \frac{d\hat{\sigma}(\bar{q}_i q_i \to \pi_B \pi_C)}{dz} = \frac{\pi\alpha_S^2(\hat{s})\beta^3}{9\hat{s}}\,\mathcal{S}_\pi T(R)\left(1-z^2\right)\left|\mathcal{D}_{gg} + \mathcal{D}_{g\rho_T}\right|^2, \tag{3.16}$$

$$\begin{aligned}
\sum_{B,C} \frac{d\hat{\sigma}(gg \to \pi_B \pi_C)}{dz} &= \frac{\pi\alpha_S^2(\hat{s})\beta}{\hat{s}}\,\mathcal{S}_\pi T(R)\Bigg\{\frac{3}{32}\,\beta^2\,z^2\left[\left|\mathcal{D}_{gg} + \mathcal{D}_{g\rho_T}\right|^2\right. \\
&\quad \left. - \frac{2\beta^2\,(1-z^2)}{1-\beta^2 z^2}\,\mathrm{Re}\,(\mathcal{D}_{gg} + \mathcal{D}_{g\rho_T}) + 2\left(\frac{\beta^2\,(1-z^2)}{1-\beta^2 z^2}\right)^2\right] \\
&\quad + \left(\frac{T(R)}{d(R)} - \frac{3}{32}\right)\left[\frac{(1-\beta^2)^2 + \beta^4\,(1-z^2)^2}{(1-\beta^2 z^2)^2}\right]\Bigg\}\,,
\end{aligned} \tag{3.17}$$

where β is the technipion velocity and $z = \cos\theta$. The symmetry factor $\mathcal{S}_\pi = 1$ for each channel of $\pi_{L\bar{Q}}\pi_{Q\bar{L}}$ and for $\pi^+_{T8}\pi^-_{T8}$; $\mathcal{S}_\pi = \frac{1}{2}$ for the identical-particle final states, $\pi^0_{T8}\pi^0_{T8}$ and $\eta_T\eta_T$. The $SU(3)$ group factors $T(R)$ and $d(R)$ for $R = 3, 8$ were defined above at Eq. (3.10). The technirho width is now the sum of the $\bar{q}q$ and gg partial widths and

$$\sum_{B,C} \Gamma(\rho_{T1} \to \pi_B\pi_C; s) = \frac{\alpha_{\rho_T}\mathcal{S}_\pi T(R)}{3}\frac{p^3}{s}\,. \tag{3.18}$$

As indicated in Table 1, pair-production rates for colored technipions with masses of a few hundred GeV are several picobarns at the Tevatron, rising to a few nanobarns at the LHC.

3.3. Signatures of Topcolor-Assisted Technicolor

The development of topcolor-assisted technicolor is still at an early stage and, so, its phenomenology is not fully formed. Nevertheless, there are three TC2 signatures that are likely to be present in any surviving model [10]–[13], [18]:

- The isotriplet of color-singlet "top-pions" π_t arising from spontaneous breakdown of the top quark's $SU(2) \otimes U(1)$ chiral symmetry;
- The color-octet of vector bosons V_8, called "colorons", associated with breakdown of the top quark's strong $SU(3)$ interaction to ordinary color;
- The Z' vector boson associated with breakdown of the top quark's strong $U(1)$ interaction to ordinary weak hypercharge.

The three top-pions are nearly degenerate. They couple to the top quark with strength m_t/F_t, where m_t is the part of the top-quark mass induced by topcolor—within a few GeV of its total mass—and $F_t \simeq 70\,\mathrm{GeV}$ [12] is the π_t decay constant.[1] If the top-pion is lighter than the top quark, then

$$\Gamma(t \to \pi_t^+ b) = \frac{(m_t^2 - M_{\pi_t}^2)^2}{32\pi m_t F_t^2}\,. \tag{3.19}$$

It is known that $B(t \to W^+b) = 0.87 \pm^{+0.13}_{-0.30}$ (stat.) $^{+0.13}_{-0.11}$ (syst.) [19]. At the 1σ level, then, $M_{\pi_t} \gtrsim 150\,\mathrm{GeV}$. At the 2σ level, the lower bound is $100\,\mathrm{GeV}$, but such a small branching ratio for $t \to W^+b$ would require $\sigma(p\bar{p} \to t\bar{t})$ at the Tevatron about 4 times the standard QCD value of $4.75^{+0.63}_{-0.68}\,\mathrm{pb}$ [20]. The $t \to \pi_t^+ b$ decay mode can be sought

[1] As far as I know, the rest of the discussion in this and the next paragraph has not appeared in print before. It certainly deserves more thought than has gone into it here. One possible starting place is the paper by Hill, Kennedy, Onogi and Yu in Ref. [11].

in high-luminosity runs at the Tevatron and with moderate luminosity at the LHC. If $M_{\pi_t} < m_t$, then $\pi_t^+ \to c\bar{b}$ through t–c mixing. It is also possible, though unlikely, that $\pi_T^+ \to t\bar{s}$ through b–s mixing.

If $M_{\pi_t} > m_t$, then $\pi_t^+ \to t\bar{b}$ and $\pi_t^0 \to \bar{t}t$ or $\bar{c}c$, depending on whether the top-pion is heavier or lighter than $2m_t$. The main hope for discovering top-pions heavier than the top quark seems to rest on the isotriplet of top-rho vector mesons, $\rho_t^{\pm,0}$. It is hard to estimate M_{ρ_t}; it may lie near $2m_t$ or closer to $\Lambda_t = \mathcal{O}(1\,\mathrm{TeV})$. They are produced in hadron collisions just as the corresponding color-singlet technirhos (Eq. (3.1)). The conventional expectation is that they decay as $\rho_t^{\pm,0} \to \pi_t^\pm \pi_t^0,\ \pi_t^+\pi_t^-$. Then, the top-pion production rates may be estimated from Eqs. (3.2) and (3.5) with $\alpha_{\rho_T} = 2.91$ and $\mathcal{C}_{AB} = 1$. The rates are not large, but the distinctive decays of top-pions help suppress standard model backgrounds.

Life may not be so simple, however. The ρ_t are not completely analogous to the ρ-mesons of QCD and technicolor because topcolor is broken near Λ_t. Thus, for distance scales between Λ_t^{-1} and $1\,\mathrm{GeV}^{-1}$, top and bottom quarks do not experience a growing confining force. Instead of $\rho_t \to \pi_t\pi_t$, it is also possible that $\rho_t^{\pm,0}$ fall apart into their constituents $t\bar{b}$, $b\bar{t}$ and $t\bar{t}$. The ρ_t resonance may be visible as a significant increase in $t\bar{b}$ production, but it won't be in $t\bar{t}$.[2]

The V_8 colorons of broken $SU(3)$ topcolor are readily produced in hadron collisions. They are expected to have a mass between 1/2–1 TeV. Colorons couple with strength $-g_S \cot\xi$ to quarks of the two light generations and with strength $g_S \tan\xi$ to top and bottom quarks, where $\tan\xi \gg 1$ [18]. Their decay rate is

$$\Gamma_{V_8} = \frac{\alpha_S M_{V_8}}{6}\left\{4\cot^2\xi + \tan^2\xi\left(1 + \beta_t(1 - m_t^2/M_{V_8}^2)\right)\right\}. \tag{3.20}$$

where $\beta_t = \sqrt{1 - 4m_t^2/M_{V_8}^2}$. Colorons may then appear as resonances in $b\bar{b}$ and $t\bar{t}$ production. For example, the $\mathcal{O}(\alpha_S)$ cross section for $\bar{q}q \to \bar{t}t$ becomes

$$\frac{d\hat{\sigma}(\bar{q}q \to \bar{t}t)}{dz} = \frac{\pi\alpha_S^2\beta_t}{9\hat{s}}\left(2 - \beta_t^2 + \beta_t^2 z^2\right)\left|1 - \frac{\hat{s}}{\hat{s} - M_{V_8}^2 + i\sqrt{\hat{s}}\,\Gamma_{V_8}}\right|^2. \tag{3.21}$$

For completeness, the $gg \to \bar{t}t$ rate is

$$\begin{aligned}\frac{d\hat{\sigma}(gg \to \bar{t}t)}{dz} = \frac{\pi\alpha_S^2\beta_t}{6\hat{s}}&\left\{\frac{1 + \beta_t^2 z^2}{1 - \beta_t^2 z^2} - \frac{(1-\beta_t^2)^2\,(1 + \beta_t^2 z^2)}{(1 - \beta_t^2 z^2)^2} - \tfrac{9}{16}(1 + \beta_t^2 z^2)\right.\\ &\left. + \frac{1 - \beta_t^2}{1 - \beta_t^2 z^2}\,(1 - \tfrac{1}{8}\beta_t^2 + \tfrac{9}{8}\beta_t^2 z^2)\right\}.\end{aligned} \tag{3.22}$$

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[2] I thank John Terning for inspiring this discussion of ρ_t decays.

A description of the search for colorons and other particles decaying to $\bar{b}b$ and $\bar{t}t$ and preliminary limits on their masses are given in Ref. [21].

Colorons have little effect on the standard dijet production rate. The situation is very different for the Z' boson of the broken strong $U(1)$ interaction.[3] In Ref. [13] a scenario for topcolor was developed in which it is necessary that the Z' couples strongly to the fermions of the first two generations as well as those of the third. The Z' probably is heavier than the colorons, roughly $M_{Z'} = 1$–$2\,\mathrm{TeV}$. Thus, at subprocess energies well below $M_{Z'}$, the interaction of Z' with all quarks is described by a contact interaction, just what is expected for quarks with substructure at the scale $\Lambda \sim 1$–$2\,\mathrm{TeV}$. This leads to an excess of jets at high E_T and invariant mass [22],[4]. An excess in the jet-E_T spectrum consistent with $\Lambda = 1600\,\mathrm{GeV}$ has been reported by the CDF Collaboration [23]. It remains to be seen whether it is due to topcolor or any other new physics. As with quark substructure, the angular and rapidity distributions of the high-E_T jets induced by Z' will be more central than predicted by QCD. The Z' will also produce an excess of high invariant mass $\ell^+\ell^-$. It will be interesting to compare limits on contact interactions in the Drell-Yan process with those obtained from jet production.

The topcolor Z' will be produced directly in $\bar{q}q$ annhilation in LHC experiments. Because the Z' is strongly coupled to so many fermions, including technifermions in the LHC's energy range, it is likely to be very broad. The development of TC2 models is at such an early stage that the Z' couplings, its width and branching fractions, cannot be predicted with confidence. These studies are underway and we can expect progress on these questions in the coming year.

4. Signatures for Quark and Lepton Substructure

The presence of three generations of quarks and leptons, apparently identical except for mass, strongly suggests that they are composed of still more fundamental fermions, often called "preons". It is clear that, if preons exist, their strong interaction energy scale Λ must be much greater than the quark and lepton masses. Long ago, 't Hooft figured out how interactions at high energy could produce essentially massless composite fermions: the answer lies in unbroken chiral symmetries of the preons *and* confinement by their strong

[3] This interaction differentiates between top and bottom quarks, helping the former develop a large mass while keeping the latter light.

"precolor" interactions [24]. There followed a great deal of theoretical effort to construct a realistic model of composite quarks and leptons (see, e.g., Ref. [25]) which, while leading to valuable insights on chiral gauge theories, fell far short of its main goal.

In the midst of this activity, it was pointed out that the existence of quark and lepton substructure will be signalled at energies well below Λ by the appearance of four-fermion "contact" interactions which differ from those arising in the standard model [22]. These interactions are induced by the exchange of preon bound states and precolor-gluons. They must be $SU(3) \otimes SU(2) \otimes U(1)$ invariant because they are generated by forces operating at or above the electroweak scale. These contact interactions are suppressed by $1/\Lambda^2$, but the coupling parameter of the exchanges—analogous to the pion-nucleon and rho-pion couplings—is not small. Thus, the strength of these interactions is conventionally taken to be $\pm 4\pi/\Lambda^2$. Compared to the standard model, contact interaction amplitudes are then of relative order $\hat{s}/\alpha_S \Lambda^2$ or $\hat{s}/\alpha_{EW}\Lambda^2$. The appearance of $1/\alpha$ and the growth with $\hat{s}$ make contact-interaction effects the lowest-energy signal of quark and lepton substructure. They are sought in jet production at hadron and lepton colliders, Drell-Yan production of high invariant mass lepton pairs, Bhabha scattering, $e^+e^- \to \mu^+\mu^-$ and $\tau^+\tau^-$ [26], atomic parity violation [27], and polarized Møller scattering [28]. Here, we concentrate on jet production and the Drell-Yan process at hadron colliders.

The contact interaction most used so far to parameterize limits on the substructure scale Λ is the product of left-handed electroweak isoscalar quark and lepton currents. Collider experiments can probe values of Λ in the 2–5 TeV range (Tevatron) to the 15–20 TeV range (LHC; see Refs. [4] and [29]). If Λ is to be this low, the contact interaction must be flavor-symmetric, at least for quarks in the first two generations, to avoid large $\Delta S = 2$ and, possibly, $\Delta B_d = 2$ neutral current interactions. We write it, the only Lagrangian we exhibit, as

$$\mathcal{L}^0_{LL} = \frac{4\pi\eta}{2\Lambda^2} \sum_{i,j=1}^{3} \left(\sum_{a=1}^{3} \bar{q}_{aiL}\gamma^\mu q_{aiL} + \mathcal{F}_\ell\, \bar{\ell}_{iL}\gamma^\mu \ell_{iL} \right) \left(\sum_{b=1}^{3} \bar{q}_{bjL}\gamma_\mu q_{bjL} + \mathcal{F}_\ell\, \bar{\ell}_{jL}\gamma_\mu \ell_{jL} \right) . \tag{4.1}$$

Here, $\eta = \pm 1$; $a, b = 1, 2, 3$ labels color; $i, j = 1, 2, 3$ labels the generations, and the quark and lepton fields are isodoublets, $q_{ai} = (u_{ai}, d_{ai})$ and $\ell_i = (\nu_i, e_i)$ (with right-handed neutrinos generally omitted). The real factor $\mathcal{F}_\ell$ is inserted to allow for different quark and lepton couplings, but it is expected to be $\mathcal{O}(1)$. The factor of $\frac{1}{2}$ in the overall strength of the interaction avoids double-counting interactions and amplitudes.

The color-averaged jet subprocess cross sections, modified for the interaction $\mathcal{L}^0_{LL}$, are given in leading order in α_S by (these formulas correct errors in Ref. [4])

$$\begin{aligned}
&\frac{d\hat\sigma(q_iq_i \to q_iq_i)}{dz} = \frac{d\hat\sigma(\bar q_i\bar q_i \to \bar q_i\bar q_i)}{dz} \\
&= \frac{\pi}{2\hat s}\left\{\frac{4}{9}\alpha_S^2\left[\frac{\hat u^2+\hat s^2}{\hat t^2} + \frac{\hat t^2+\hat s^2}{\hat u^2} - \frac{2}{3}\frac{\hat s^2}{\hat t\hat u}\right] + \frac{8}{9}\alpha_S\frac{\eta}{\Lambda^2}\left[\frac{\hat s^2}{\hat t}+\frac{\hat s^2}{\hat u}\right] + \frac{8}{3}\frac{\hat s^2}{\Lambda^4}\right\}; \\
&\frac{d\hat\sigma(q_i\bar q_i \to q_i\bar q_i)}{dz} \\
&= \frac{\pi}{2\hat s}\left\{\frac{4}{9}\alpha_S^2\left[\frac{\hat u^2+\hat s^2}{\hat t^2} + \frac{\hat u^2+\hat t^2}{\hat s^2} - \frac{2}{3}\frac{\hat u^2}{\hat s\hat t}\right] + \frac{8}{9}\alpha_S\frac{\eta}{\Lambda^2}\left[\frac{\hat u^2}{\hat t}+\frac{\hat u^2}{\hat s}\right] + \frac{8}{3}\frac{\hat u^2}{\Lambda^4}\right\}; \\
&\frac{d\hat\sigma(q_i\bar q_i \to q_j\bar q_j)}{dz} = \frac{\pi}{2\hat s}\left\{\frac{4}{9}\alpha_S^2\left[\frac{\hat u^2+\hat t^2}{\hat s^2}\right] + \frac{\hat u^2}{\Lambda^4}\right\}; \\
&\frac{d\hat\sigma(q_i\bar q_j \to q_i\bar q_j)}{dz} = \frac{\pi}{2\hat s}\left\{\frac{4}{9}\alpha_S^2\left[\frac{\hat u^2+\hat s^2}{\hat t^2}\right] + \frac{\hat u^2}{\Lambda^4}\right\}; \\
&\frac{d\hat\sigma(q_iq_j \to q_iq_j)}{dz} = \frac{d\hat\sigma(\bar q_i\bar q_j \to \bar q_i\bar q_j)}{dz} = \frac{\pi}{2\hat s}\left\{\frac{4}{9}\alpha_S^2\left[\frac{\hat u^2+\hat s^2}{\hat t^2}\right] + \frac{\hat s^2}{\Lambda^4}\right\}.
\end{aligned} \tag{4.2}$$

For this LL-isoscalar interaction, the interference term (η/Λ^2) in the hadron cross section is small and the sign of η is not very important. Interference terms may be non-negligible in contact interactions with different chiral, flavor, and color structures. In all cases, the main effect of substructure is to increase the rate of centrally-produced jets. Seeing this in the jet angular distribution is important for confirming the presence of contact interactions.

The modified cross sections for the Drell-Yan process $\bar q_i q_i \to \ell_j^+\ell_j^-$ is

$$\frac{d\hat\sigma(\bar q_iq_i \to \ell_j^+\ell_j^-)}{dz} = \frac{\pi\alpha^2}{6\hat s}\left[\mathcal{A}_i(\hat s)\left(\frac{\hat u}{\hat s}\right)^2 + \mathcal{B}_i(\hat s)\left(\frac{\hat t}{\hat s}\right)^2\right], \tag{4.3}$$

where

$$\begin{aligned}\mathcal{A}_i(\hat{s}) =& \left[Q_i + \frac{4}{\sin^2 2\theta_W}\left(T_{3i} - Q_i \sin^2\theta_W\right)\left(\tfrac{1}{2} - \sin^2\theta_W\right)\left(\frac{\hat{s}}{\hat{s} - M_Z^2}\right) - \frac{\mathcal{F}_\ell \eta \hat{s}}{\alpha\Lambda^2}\right]^2 \\ &+ \left[Q_i + Q_i \tan^2\theta_W\left(\frac{\hat{s}}{\hat{s} - M_Z^2}\right)\right]^2; \\ \mathcal{B}_i(\hat{s}) =& \left[Q_i - \frac{1}{\cos^2\theta_W}\left(T_{3i} - Q_i\sin^2\theta_W\right)\left(\frac{\hat{s}}{\hat{s} - M_Z^2}\right)\right]^2 \\ &+ \left[Q_i - \frac{1}{\cos^2\theta_W} Q_i\left(\tfrac{1}{2} - \sin^2\theta_W\right)\left(\frac{\hat{s}}{\hat{s} - M_Z^2}\right)\right]^2.\end{aligned} \tag{4.4}$$

The angular distribution of the ℓ^- relative to the incoming quark is an important probe of the contact interaction's chiral structure. Measuring this distribution is easy in a $\bar{p}p$ collider such as the Tevatron since the hard quark almost always follows the proton direction. If the scale Λ is high so that parton collisions revealing the contact interaction are hard, the quark direction can also be determined with reasonable confidence in a pp collider. At the LHC, the quark in a $\bar{q}q$ collision with $\sqrt{\hat{s}/s} \gtrsim 1/20$ is harder than the antiquark, and its direction is given by the boost rapidity of the dilepton system, at least 75% of the time. The charges of $\mathcal{O}(1\,\mathrm{TeV})$ muons can be well-measured even at very high luminosity in the detectors being designed for the LHC. These two ingredients are needed to insure a good determination of the angular distribution [29].

It is important to study the effects of contact interactions with chiral, flavor and color structures different from the one in Eq. (4.1). Such interactions can give rise to larger (or smaller) cross sections for the same Λ because they have more terms or because they interfere more efficiently with the standard model. Thus, it will be possible to probe even higher values of Λ for other structures. Other forms can also give rise to $\ell^\pm\nu$ final states. Searching for contact interactions in these modes is more challenging than in $\ell^+\ell^-$, but it is very useful for untangling flavor and chiral structures [29]. Events are selected which contain a single high-p_T charged lepton, large missing E_T and little jet activity. Even though the parton c.m. frame cannot be found in this case, it is still possible to obtain information on the chiral nature of the contact interaction by comparing the rapidity distributions, $|\eta_{\ell^+}|$ and $|\eta_{\ell^-}|$ of the high-p_T leptons. For example, if the angular distribution in the process $d\bar{u} \to \ell^-\bar{\nu}$ between the incoming d-quark and the outgoing ℓ^- is $(1+\cos\theta)^2$, then $|\eta_{\ell^-}|$ is pushed to larger values because the d-quark is harder than the $\bar{u}$-quark and the ℓ^- tends to be produced forward. Correspondingly, in $u\bar{d} \to \nu\ell^+$, the $|\eta_{\ell^+}|$ distribution would be squeezed to smaller values.

5. Conclusions and Acknowledgements

Many theorists are convinced that low-energy supersymmetry is intimately connected with electroweak symmetry breaking and that its discovery is just around the corner [30]. One often hears that searches for other TeV-scale physics are a waste of time. Experimentalists know better. The vast body of *experimental* evidence favors no particular extension of the standard model. Therefore, all plausible approaches must be considered. Detectors must have the capability—and experimenters must be prepared—to discover whatever physics is responsible for electroweak and flavor symmetry breaking. To this end, we have summarized the principal signatures for technicolor, extended technicolor and quark-lepton substructure. Table 1 lists sample masses for new particles and their production rates at the Tevatron and LHC. We hope this summary helps in-depth studies of strong TeV-scale dynamics get underway at Snowmass.

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Process	Sample Mass (GeV)	$\sigma_{\rm TeV}$(pb)	$\sigma_{\rm LHC}$(pb)
$\rho_{T1} \to W_L \pi_T$ [1]	$220(\rho_{T1})$, $100(\pi_T)$	5	35
$\rho_{T1} \to \pi_T \pi_T$ [1]	$220(\rho_{T1})$, $100(\pi_T)$	5	25
$gg \to \pi_T^0 \to b\bar{b}$ [2]	100	300/5000	$7000/10^5$
$gg \to \eta_T \to t\bar{t}$ [3]	400	3/3	2000/600
$gg \to \pi_T \pi_T$ [4]	100	0.2	600
$\rho_{T8} \to$ jet jet [5]	$250(\rho_{T8})$	700/5000	$1.5 \times 10^4/1.5 \times 10^5$
	$500(\rho_{T8})$	10/40	2000/6000
$\rho_{T8} \to \pi_{T8} \pi_{T8}$ [6]	$550(\rho_{T8}), 250(\pi_{T8})$	2	2000
$\rho_{T8} \to \pi_{Q\bar{L}} \pi_{L\bar{Q}}$ [6]	$550(\rho_{T8}), 200(\pi_{Q\bar{L}})$	2	1000
$V_8 \to t\bar{t}$ [7]	500	8/3	100/600
Λ reach [8]	5 TeV (TeV), 20 TeV (LHC)	$10\,\mathrm{fb}^{-1}$	$100\,\mathrm{fb}^{-1}$

[1] $F_T = F_\pi/3 = 82\,\mathrm{GeV}$ was used.

[2] $F_T = 50\,\mathrm{GeV}$ used. Cross section is integrated over $\mathcal{M}_{b\bar{b}} = 90$–$110\,\mathrm{GeV}$.

[3] $F_T = 50\,\mathrm{GeV}$ and $m_t = 175\,\mathrm{GeV}$ were used. The greatly increased LHC cross section is due to the rapid growth of gluons at small-x.

[4] Cross sections for a multiscale model with 250 GeV π_{T8} and 200 GeV $\pi_{Q\bar{L}}$ intermediate states.

[5] Jet energy resolution of $\sigma(E)/E = 100\%/\sqrt{E}$ is assumed and cross sections integrated over $\pm\Gamma$ about resonance peak. Jet angles are limited by $\cos\theta^* < \frac{2}{3}$ and $|\eta_j| < 2.0$ (Tevatron) or 1.0 (LHC).

[6] Cross sections per channel are quoted.

[7] $\tan\xi = \sqrt{2\pi/3\alpha_S}$ was used, corresponding to a critical topcolor coupling strength.

[8] Estimated Λ reaches in dijet and dilepton production are for the indicated luminosities.

Process	References	CDF Contact	DØ Contact
$\rho_{T1} \to W_L \pi_T$	[6], [14]	toback@fnald	hobbs@d0sgi4 womersley@fnald0
$\rho_{T1} \to \pi_T \pi_T$	[6], [14]	troconiz@fnald	womersley@fnald0
$gg \to \pi_T^0 \to b\bar{b}$	[4],[15],[21]	benlloch@fnald	johns@fnald0 zieminski@fnald0
$gg \to \eta_T \to t\bar{t}$	[4],[15],[21]	kirsten@fnald	klima@fnal
$gg \to \pi_T \pi_T$	[16]	troconiz@fnald	womersley@fnald0
$\rho_{T8} \to$ jet jet	[6], [17]	rharris@cdfsga chaowei@fnald	bertram@fnald0
$\rho_{T8} \to \pi_{T8} \pi_{T8}$	[6]	troconiz@fnald	womersley@fnald0
$\rho_{T8} \to \pi_{Q\bar{L}} \pi_{L\bar{Q}}$	[6]	baumann@fnald	womersley@fnald0
V_8, $Z' \to t\bar{t}$, $b\bar{b}$	[18], [21]	kirsten@fnald rharris@cdfsga	klima@fnal womersley@fnald0
Λ reach	[22],[4],[23] [29]	rharris@cdfsga (jets) maeshima@fnald (leptons)	hpiekarz@fnald0 wightman@fnald0 (jets) eppley@fnald0 (leptons)

Table 1. Sample cross sections for technicolor signatures at the Tevatron and LHC. Cross sections may vary by a factor of 10 for other masses and choices of the parameters. K-factors of 1.5–2 are expected, but not included. Signal over background rates are quoted as S/B. $N_{TC} = 4$ in all calculations; cross sections generally grow with N_{TC}. All e-mail addresses are name@node.fnal.gov unless otherwise noted.

Model	C_3	C_8	D_3	D_8
One–Family $\pi_T\pi_T$	$\frac{10}{3}$	$\frac{1}{3}$	$\frac{16}{9}M_3^2$	$\frac{4}{9}M_8^2$
Multiscale $\pi_{\bar{Q}Q}\pi_{\bar{Q}Q}$	$\frac{8}{3}$	$\frac{4}{3}$	$\frac{32}{9}M_3^2$	$\frac{16}{9}M_8^2$
Multiscale $\pi_{\bar{L}L}\pi_{\bar{L}L}$	8	0	$\frac{16}{3}(2M_{\pi_T}^2 - M_3^2)$	0

Table 2. The factors C_R and D_R in Eq. (3.10) for $gg \to \pi_T\pi_T$ for the one–family model and a multiscale technicolor model containing a doublet of techniquarks Q and technileptons L (see Ref. [16]). The masses of intermediate color-triplet and octet technipions are M_3 and M_8.